

¹ Impact of assimilated and interactive aerosol on ² Tropical Cyclogenesis.

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3 This article investigates the impact of Saharan dust on the development
4 of tropical cyclones in the Atlantic. A global data assimilation and forecast
5 system, the NASA GEOS-5, is used to assimilate all satellite and conven-
6 tional data sets used operationally for numerical weather prediction. In ad-
7 dition, this new GEOS-5 version includes assimilation of aerosol optical depth
8 from the Moderate Resolution Imaging Spectroradiometer (MODIS). The
9 analysis so obtained comprises atmospheric quantities and a realistic 3-d aerosol
10 and cloud distribution, consistent with the meteorology and validated against
11 Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO)
12 and CloudSat data. These improved analyses are used to initialize GEOS-
13 5 forecasts, explicitly accounting for aerosol direct radiative effects and their
14 impact on the atmospheric dynamics. Parallel simulations with/without aerosol
15 radiative effects show that effects of dust on static stability increase with time,
16 becoming highly significant after day 5 and producing an environment less
17 favorable to tropical cyclogenesis.

1. Introduction

The possibility that the Saharan Air Layer (SAL) exerts some control on weather systems over the tropical Atlantic has been contemplated since the early '70s [e.g., Carlson and Prospero, 1972]. Among various studies, Karyampudi and Pierce [2002] conjectured that the SAL effect on the development of waves into tropical cyclones (TCs) could be modulated by seasonal precipitation over the Sahel, with a negative (i.e., suppressing) impact occurring only in dry seasons. Dunion and Velden [2003] attributed to the SAL a generally unfavorable role on tropical cyclogenesis, finding supported by a number of other studies [e.g., Sun et al. 2009]. On the other hand, Braun [2011] presents an overall critical view of the SAL as a TC-suppressing agent and suggests, among other concerns, the possibility that it may be dry air of non-Saharan origin that actually plays an inhibiting role, attributed erroneously to the SAL.

An important contribution to this ongoing debate stems from the ability of realistically simulating the aerosol radiative effects on the tropical atmosphere. The forerunner study [Tompkins et al., 2005] demonstrated the improvement caused by insertion of climatologically-varying aerosols in a global modeling setting. Since then, progress has been made to simulate increasingly realistic aerosols. Among several studies, Reale et al. [2011, hereafter RLD11] have shown that simulated aerosols, realistically varying with the meteorology and interacting with the atmospheric dynamics (instead of being climatologically prescribed), further improve the representation of the African Easterly Jet (AEJ).

A further step is represented by the ability to *objectively* define the SAL through a 3-dimensional dust distribution constrained by assimilated observed aerosols: i.e., to create a SAL analysis as a product of a DAS (Data Assimilation System). Until now, statements on the SAL borders have been limited by qualitative interpretation of satellite imagery and a categorical SAL definition based on a subjectively chosen threshold of aerosol optical depth (AOD). A degree of subjectivity is also introduced by the incomplete data coverage, which makes it necessary to arbitrarily extrapolate the edges of the SAL across data-void areas.

NASA has attempted to overcome these limitations by developing a global assimilation capability of space-based AOD measurements from the Moderate Resolution Imaging Spectroradiometer (MODIS). This new system creates, as part of the atmospheric analysis, a continuous dust distribution which is consistent with aerosol observations, meteorological observations and physical constraints of the atmosphere. In this study, assimilated AOD from MODIS and interactive aerosol modeling are used together in a global framework to investigate the effect of SAL on TC genesis and development.

2. Model and Experiments

This work uses the NASA global data assimilation and forecasting system GEOS-5, developed by the Global Modeling Assimilation Office (GMAO). The GEOS-5 merges a modified version of the National Centers for Environmental Predictions (NCEP) Gridpoint Statistical Interpolation (GSI) analysis algorithm (e.g. Wu et al., [2002]) with the NASA atmospheric global forecast model, as documented in Rienecker et al., [2008]. From the 2008 version, many notable improvements have been applied to the GEOS-5, including

the aerosol radiative effects for dust, sea salt, carbonaceous and sulfate aerosols, made possible by the Goddard Chemistry, Aerosol, Radiation and Transport Model (GOCART) module. The GOCART includes aerosol specific processes such as emission, deposition, simplified sulfate chemistry [Colarco et al. 2010], while aerosol advection, diffusion and convection are computed by the host GEOS-5 model. RLD11 used this aerosol modeling capability, but relied on dust concentrations which were dictated by the dust emissions parameterized in the model. While a comparison with observations showed that the aerosol distribution in the initial conditions was realistic, it was nevertheless simulated, and therefore not directly constrained by observations as in a true ‘analysis’.

In contrast, this article documents an important advance: the ability to *directly assimilate* AOD derived from MODIS. In near-real time, the GEOS-5 DAS includes assimilation of AOD observations from the MODIS sensor on both the Terra and Aqua satellites. Based on the work of Zhang and Reid [2006] and Lary [2010], a back-propagation neural network has been developed to correct observational biases related to cloud contamination, surface parameterization, and aerosol microphysics, using Aerosol Robotic Network (AERONET) measurements. This empirical algorithm retrieves AOD directly from cloud-cleared MODIS reflectances. On-line quality control is performed with the adaptive buddy check of Dee et al. [2001], with observation and background errors estimated using the maximum likelihood approach of Dee and da Silva [1999]. Following a multi-channel AOD analysis, three-dimensional analysis increments are produced using local displacement ensembles intended to represent misplacements of the aerosol plumes. This new feature allows the GEOS-5 DAS to produce, together with the conventional analysis of meteoro-

logical fields, a three-dimensional analysis of dust distribution that is 1) consistent with meteorology at all times and 2) constantly constrained by MODIS observations.

This is an important difference with respect to RLD11, leading to a more accurate representation of the dust distribution and its impact on the atmospheric circulation. It also represents an advance in the field, not yet implemented at this high resolution and in a fully coupled mode in any operational forecasting system.

In this work, a one month-long high-resolution (horizontal: $0.25^{\circ} \times 0.3125^{\circ}$, vertical: 72 layers) data assimilation is performed with the GEOS-5 DAS, to cover the period from 15 August 2006 to 17 September 2006, corresponding to the well-studied special observing phase (SOP-3) of the NASA African Monsoon Multidisciplinary Analysis (NAMMA) campaign. All conventional and satellite observations used operationally at that time are assimilated, in addition to MODIS-derived AOD. The result is a month of 3-hourly high-quality global meteorological analyses and three-dimensional dust analyses, without data-void areas.

From these analyses, two sets of 31 5-day forecasts at the same resolution are initialized daily at 21 Z, starting from 15 August 2006. The two forecast sets differ by the exclusion (*NOA*, no aerosol) or inclusion (*IAA*, interactive aerosol) of the aerosol radiative effects. The length of all the integrations initialized between August 20 and August 28, a period noteworthy for the interaction of intense dust outbreaks with African Easterly Waves (AEWs), is extended to ten days. The increased forecast length allows for a clearer differentiation between the *NOA* and *IAA* forecasts (which are both initialized from the same analyses), by allowing for a longer spin-up time. Even if we refer to these 10-day

103 integrations as ‘forecasts’ we need to clarify that their purpose is to understand physical
104 processes affecting tropical development and not to investigate forecast skill (which is the
105 subject of a future manuscript centered on validation and forecast skill assessment).

3. Results

106 The impact of interactive aerosols (hereafter Δ_{NOA}^{IAA}) as a function of time t can be de-
107 fined as a difference $\Delta q(t) = q_{IAA}(t) - q_{NOA}(t)$ of a 3-dimensional meteorological quantity
108 $q(t)$ such as temperature or wind, computed in the *IAA* and *NOA* simulations respec-
109 tively. As noted in RLD11, $\Delta_{NOA}^{IAA}(t)$ is difficult to assess at an instantaneous time because
110 of the intrinsically chaotic nature of the dynamics associated with dust radiative forcing,
111 inhomogeneously distributed and rapidly changing in space and time, and the superpo-
112 sition of the diurnal cycle. In addition, it needs to be clarified that the effect of dust on
113 atmospheric thermal structure is *always* present in the initial conditions, even of the *NOA*
114 runs. In fact, if dust is present in the real atmosphere at a given time, it is impossible to
115 remove its previous effect on temperature and stability from the initial conditions of an
116 integration. It is only possible to gradually remove the effect of dust from a forecast *after*
117 the initial state, by running an experiment with a *NOA* configuration for a sufficiently
118 long time. However, even in this case, the impact $\Delta_{NOA}^{IAA}(t)$ increases slowly as a function
119 of integration time. In RLD11, and in this study as well (not shown), a discernible impact
120 can be produced by averaging $\Delta_{NOA}^{IAA}(t)$ through forecast time and across the longitudes
121 of the areas which are affected by high dust concentration. RLD11 main impact was a
122 northward and upward shift of the AEJ, in agreement with other studies (i.e., Wilcox et

123 al. [2010]) and an improvement in regional forecast skill. However, no evident effect on
124 cyclogenesis was found in RLD11.

125 In contrast, the main result of this work is that after sufficient time from the initial
126 conditions, the dynamical effects of the different radiative forcing imposed by the presence
127 of aerosols start affecting the cyclogenetic process. To this purpose, an example of a clear
128 signal associated with a major dust outbreak is presented. We select the strong outbreak
129 moving from Africa to the Atlantic between 25 and 28 August 2006, which was observed
130 during the NAMMA SOP-3 and discussed in detail by Reale et al. [2009] and Reale and
131 Lau [2010]. These studies did not have aerosol modeling and assimilation capabilities,
132 but investigated the SAL temperature structure (improved by the assimilation of ad-hoc
133 Atmospheric Infrared Sounder (AIRS) temperature profiles) with the aid of the GEOS-5,
134 whose finite-volume dynamics is particularly suitable to maintain fine thermal features
135 and avoid unrealistic dispersion. Their findings suggested the existence of a temperature
136 dipole associated with the dust outbreak: relatively warm at 600-700 hPa and cooler at
137 about 900 hPa or below.

138 Figure 1 shows the westward progression of the same strong dust outbreak, intercepting
139 the African coastline at about $15^{\circ} - 30^{\circ}N$, and also the interaction of the dust plume with
140 a broad and weak low pressure area, as represented in the dust analysis produced by the
141 GEOS-5 assimilation between 26 and 27 August 2006.

142 The complete validation problem is very complex and is beyond the scope of this article,
143 being the subject of a separate study, which will include an assessment of the dust analysis
144 against satellite observations, and the evaluation of the model's forecast skill (with and

without aerosol effects) with a variety of metrics. However, a preview of the validation effort is provided. Data from the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) and CloudSat, which have allowed a much more accurate understanding of aerosols' optical properties [e.g., Omar et al., 2009] and clouds, are being used for validation. Figures FS1, FS2 and FS3 show comparisons between satellite observations and the corresponding model-generated satellite signals derived from the multi-sensor satellite simulator (documented in Matsui et al. [2013]), which can extract cloud and aerosol profiles from the GEOS-5 as if they were measured from the CALIPSO and CloudSat. The evaluation produced with the satellite simulator shows that the GEOS-5 realistically captured cloud- and mineral dust-affected Lidar backscatter, color ratio, and radar reflectivity in comparison with the observations from CALIPSO and CloudSat sensors (please see supplemental material for a more detailed discussion) over both land and ocean. This preliminary assessment confirms that GEOS5 is able to produce realistic cloud and mineral dust profiles, which is an essential prerequisite for properly simulating the effects of dust on the atmospheric dynamics.

As for the impact on the dynamics, some effects are noted on wind and temperature, when averaged across the forecast time and across longitudes (not shown), as in RLD11. However, since the focus is on TC genesis, the formation of low-level circulations is investigated here in each of the 31 forecasts for both NOA and IAA cases. As a measurement of the TC genesis activity, the minimum value reached by sea-level pressure (SLP_{min}), and the maximum value reached by 850 hPa relative vorticity (ζ_{max}), as a function of forecast time, are computed over a domain ranging from $5^{\circ}N$ to $20^{\circ}N$ and from $40^{\circ}W$ to $18^{\circ}W$.

167 The domain is shown in Fig. 1 and is chosen so as to partly overlap with the eastern side
168 of the so-called Main Development Region. It is slightly more extended to the east (up
169 the African coast) and to the south, where most of the disturbances affected by high dust
170 concentration are noted.

171 For each individual forecast, a time series of $SLP_{\min}(t)$ and $\zeta_{\max}(t)$ is obtained. At any
172 given forecast time t , the values of $SLP_{\min}^{IAA}(t)$ and $\zeta_{\max}^{IAA}(t)$ (or $SLP_{\min}^{NOA}(t)$ and $\zeta_{\max}^{NOA}(t)$)
173 represent the ‘signature’ of the most intense low-level circulation created by the model
174 in a *IAA* (or *NOA*) configuration within that domain. The impact of the aerosol within
175 the selected domain can thus be assessed by comparing the time series $SLP_{\min}^{IAA}(t)$ against
176 $SLP_{\min}^{NOA}(t)$, and $\zeta_{\max}^{IAA}(t)$ against $\zeta_{\max}^{NOA}(t)$. These do not differ significantly for $t < 120h$,
177 indicating an overall negligible aerosol impact on cyclogenesis during the first 5 days of
178 the forecast (not shown).

179 As explained before, this is reasonable, because both *NOA* and *IAA* sets of forecasts
180 are initialized from the same analysis. Even if the effects of dust are not computed
181 in the *NOA* integrations, it is impossible to remove them from the initial conditions,
182 because these effects are still present in initial state, whenever dust is present (as in
183 this case). So the *NOA* and *IAA* integrations need some spin-up time for the different
184 representation of the physical processes to produce a stronger effect on the dynamics. In
185 order to verify whether the aerosol impact $\Delta_{NOA}^{IAA}(t)$ grows with time and meaningfully
186 affects the cyclogenetic processes, the forecasts initialized between the 20th and the 28th
187 are extended up to ten days. We thus compute the SLP_{\min} and (ζ_{\max}) time series as a
188 function of integration time over the previously referred domain, for each of the 8 *IAA*

189 and corresponding *NOA* ten-day forecasts. The 24-hour running means of all the 8 *NOA*
 190 time series are averaged as function of integration time t , and compared in Fig. 2 to the
 191 corresponding *IAA* ones: the difference $\zeta_{max}^{IAA} - \zeta_{max}^{NOA}$ is statistically significant at 99%
 192 beyond day 5. Consistently, the difference $SLP_{min}^{IAA}(t) - SLP_{min}^{NOA}(t)$ becomes significantly
 193 positive, and does not ever change sign at any time t after day 5 (not shown), indicating
 194 that if closed circulations form in the *NOA* environment they tend to have deeper center
 195 pressures. In FS4, three individual forecasts, selected among the 8 averaged in Fig. 2,
 196 emphasize the different $\Delta_{NOA}^{IAA}(t)$ when strong, moderate or no TC genesis occurs within
 197 the domain. If no disturbance forms in the domain throughout a single forecast, or if
 198 a disturbance exists but no dust is present, there cannot be an impact on TC genesis:
 199 the simultaneous presence of dust and ongoing cyclogenetic processes is necessary for a
 200 significant $\Delta_{NOA}^{IAA}(t)$ in an individual forecast.

201 Figure 3 showcases one of the forecasts and provides a possible mechanism. Both
 202 integrations produce a cyclone, but the *NOA* case is much deeper and lagging behind
 203 the *IAA*. The cyclone is surrounded by dust almost entirely, although the location of the
 204 center is in a dust-free area. A zonal vertical cross section at $18^\circ N$ is taken across the
 205 center of the storm in the *IAA* case and shows the *IAA* temperature anomaly, obtained by
 206 subtracting the mean temperature at the same latitude of a section spanning from $80^\circ W$
 207 to 20° in longitude. The warm core of the hurricane (at about $33^\circ W$) is recognizable,
 208 together with the dust-induced temperature dipoles on both sides of it. As in RLD11, a
 209 warming is noted in correspondence to the dust level, and a slight cooling below, which
 210 increases the static stability at a close distance from the storm, particularly to the west

211 of its center. The last panel of Fig. 3 is obtained by averaging the last 72 hours of the
212 simulation on a zonal section at $22^{\circ}N$, so as to intersect the dust plume that is skirting the
213 storm to the north throughout its westward progression. The cross-section illustrates the
214 physical role of dust over the 3 days preceding the snapshot. An evident thermal anomaly
215 is associated with the protruding dust plume towards the ocean, with strong warming at
216 the dust levels, and some cooling on the near-surface levels. The anomalous temperature
217 dipole, which increases the static stability and reduces upward moisture flux in the mid-
218 and low-tropospheric environment surrounding the TC, is the main reason for the overall
219 weaker cyclones in the *IAA* experiments. Moreover, since the sea-surface temperature is
220 prescribed and the ocean is unable to adjust to the reduction in shortwave radiation, the
221 low-level cooling is probably underestimated.

4. Discussion and concluding remarks

222 The debate on the possible role of dust on tropical cyclogenesis is complex, due to
223 the inherent difficulties in rigorously proving either argument. Even between studies
224 suggesting a negative SAL effect on TC genesis, there is no overwhelming agreement
225 on whether the intrinsically dryness and high heat content of the SAL dominate the
226 interaction with AEWs, or rather the dust radiative heating. More complexity is added
227 by the treatment of the indirect effects of dust and its microphysical properties [e.g., Van
228 den Heever, 2011; Tao et al. 2012], which however are not discussed in this study.

229 If we focus on radiative effects only, the debate on their impact often becomes tainted
230 by some degree of subjectivity due to the difficulty of objectively quantifying the SAL and
231 simulating its effect with a realistic distribution of dust. The introduction of assimilated

232 aerosols into a high-resolution global model (already noteworthy for its accurate represen-
233 tation of the tropical atmosphere) allows us to have a better understanding on the aerosol
234 direct radiative effect and its feedback into the dynamics. With these new capabilities we
235 have shown that aerosols radiative effects, computed during a strong dust outbreak, make
236 the environment less conducive to tropical cyclone development. The result is statistically
237 significant and has important implications for medium-range weather forecasting in the
238 tropical Atlantic region.

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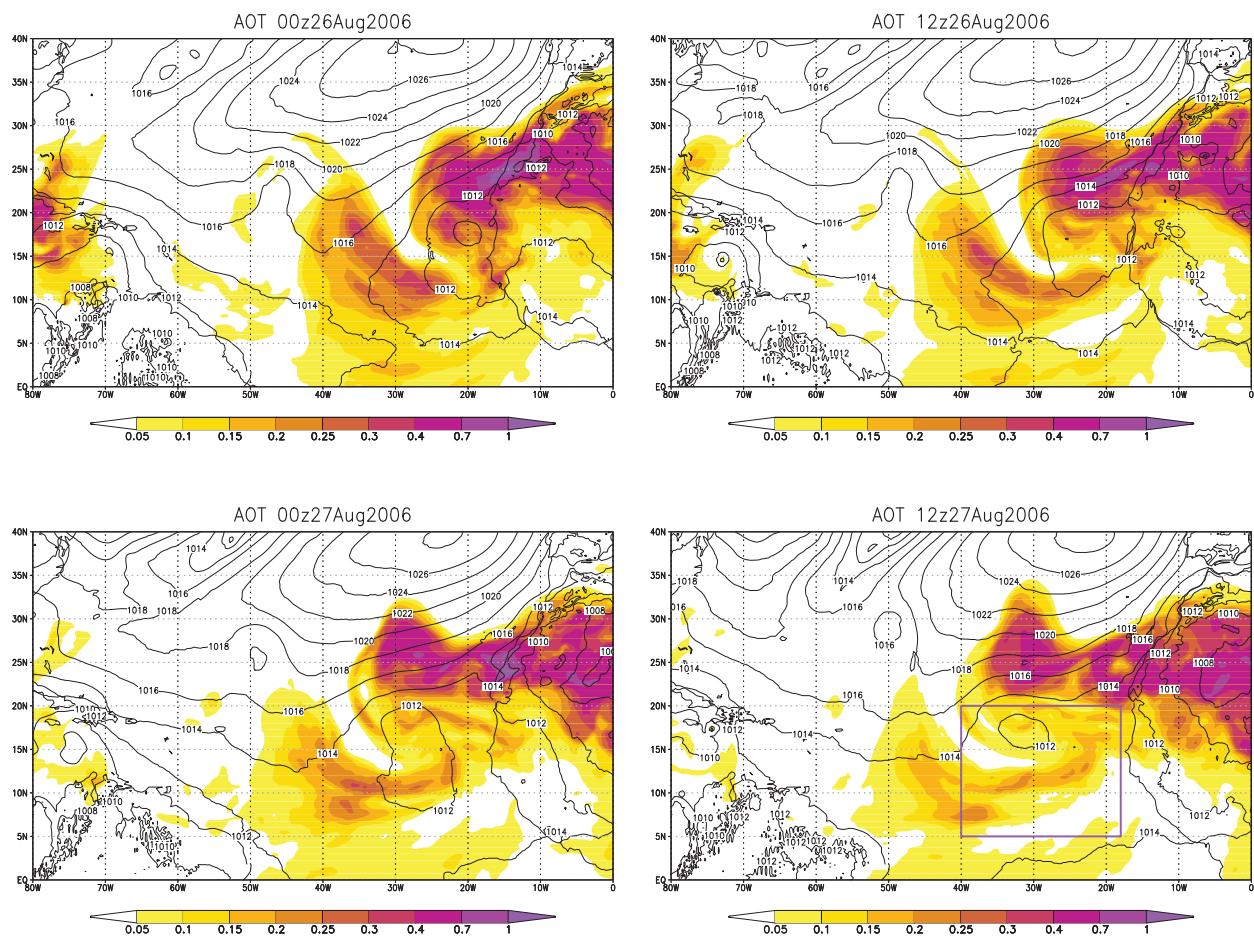


Figure 1. Analysis of Aerosol Optical Depth from the GEOS-5, obtained by assimilation of MODIS optical depth, for 26 August and 27 August 2006.

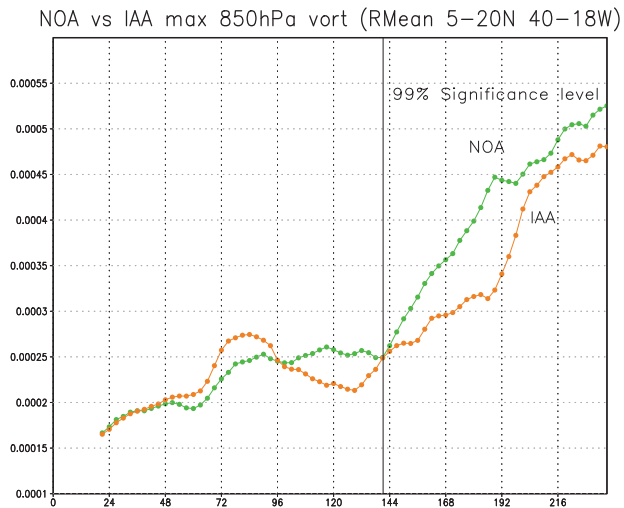


Figure 2. Running 24-hour mean, as a function of forecasting time, for eight NOA and eight IAA forecasts of 850 hPa maximum vorticity. The vorticity maxima are detected at each time step over a chosen domain ($5^{\circ}N - 20^{\circ}N, 40^{\circ}W - 18^{\circ}W$), shown in Fig. 1 (lower right panel) which is affected by a strong dust outbreak during the time. The eight forecasts are initialized from 21z19 August to 21z27 August. After day 6, the difference IAA minus NOA is statistically significant at 99%.

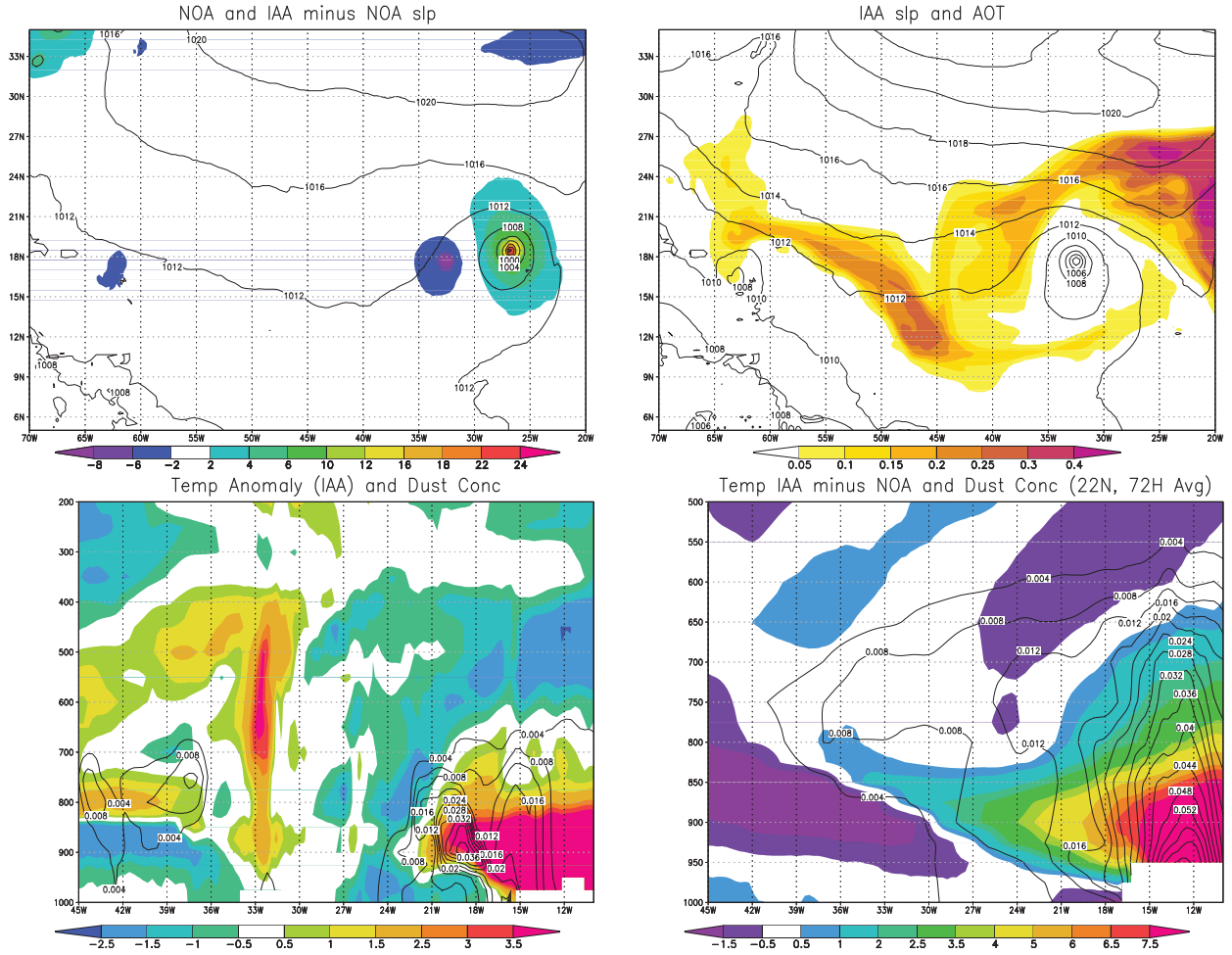


Figure 3. Upper panels: ten day forecast for 18z 2006 5 September, initialized at 21z 26Aug 2006 of NOA slp (hPa, solid) and IAA minus NOA slp departure (shaded, left), and IAA slp (solid) and AOD (shaded, right). Lower left: dust concentration and *IAA* temperature anomaly ($^{\circ}\text{C}$), obtained by subtracting the mean *IAA* temperature from 60°W to 20°W at 18°N. Lower right: 7 to 10 day forecast, 72 hour average, of *IAA* minus *NOA* temperature (shaded) and corresponding mean dust concentration, at 22°N.